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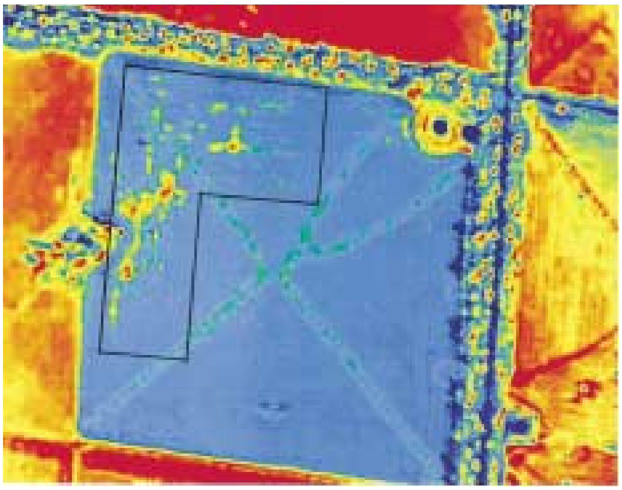

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Modelling crop growth and yield under the environmental changes induced by windbreaks. 1. Model development and validation

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Abstract. Yield advantages of crops grown behind windbreaks have often been reported, but underlying principles responsible for such changes and their long-term consequences on crop productivity and hence farm income have rarely been quantified. Physiologically and physically sound simulation models could help to achieve this quantification. Hence, the APSIM systems model, which is based on physiological principles such as transpiration efficiency and radiation use efficiency (termed here $APSIM_{TE}$), and the Soil Canopy Atmosphere Model (SCAM), which is based on the Penman–Monteith equation but includes a full surface energy balance, were employed in developing an approach to quantify such windbreak effects. This resulted in a modified APSIM version ($APSIM_{EO}$), containing the original Penman equation and a calibration factor to account for crop- and site-specific differences, which were tested against field data and simulations from both the standard $APSIM_{TE}$ and SCAM models.

The $APSIM_{EO}$ approach was tested against field data for wheat and mungbean grown in artificial enclosures in south-east Queensland and in south-east Western Australia. For these sheltered conditions, daily transpiration demand estimates from $APSIM_{EO}$ compared closely to SCAM. As the $APSIM_{EO}$ approach needed to be calibrated for individual crops and environments, average transpiration demand for open field conditions predicted by $APSIM_{EO}$ for a given site was adjusted to equal that obtained using $APSIM_{TE}$ by modifying a calibration parameter β. For wheat, a β-value of 1.0 resulted in best fits for Queensland, while for Western Australia a value of 0.85 was necessary. For mungbean a value of 0.92 resulted in the best fit (Qld). Biomass and yields simulated by $APSIM_{TE}$ and the calibration $APSIM_{EO}$ for wheat and mungbean grown in artificial enclosures were generally distributed around the 1:1 line, with R^2 values ranging from 0.92 to 0.97.

Finally, $APSIM_{EO}$ was run at 2 sites using long-term climate data to assess the likely year-to-year variability of windbreak effects on crop yields. Assuming a 70% reduction in wind speed as representing the maximum potential windbreak effect, the average yield improvement for the Queensland site was 13% for wheat and 3% for mungbean. For wheat at the WA site the average yield improvement from reduced wind speed was 5%. In any year, however, effects varied from negative, neutral to positive, highlighting the highly variable nature of the expression of windbreak effects.

This study has shown how physical and biological modelling approaches can be combined to aid our understanding of systems processes. Both the environmental physics perspective and the biological perspective have shortcomings when issues that sit at the interface of both approaches need to be addressed. While the physical approach has clear advantages when investigating changes in physical parameters such as wind speed, vapour pressure deficit (VPD), temperature or the energy balance of the soil–plant–atmosphere continuum, it cannot deal with complex, biological systems adequately. Conversely, the crop physiological approach can handle such biological interactions in a scientific and robust way while certain atmospheric processes are not considered. The challenge was not to try and capture all these effects in 1 model, but rather to structure a modelling approach in a way that allowed for inclusion of such processes where necessary.

Introduction

Trees on farms are associated with long-term benefits ranging from reduced potential for soil erosion to alleviating salinity problems (Bird *et al*. 1992; Cleugh *et al*. 2002). However, trees grown on arable lands reduce the area available for cropping and also act as competitors with adjacently sown crops for potentially scarce resources such as water, light and nutrients. Such tree–crop competition often reduces crop yields in the competition zone. This competition effect may be compensated by beneficial

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impacts of windbreaks on crop productivity outside the immediate competition zone. Such beneficial effects have been reported frequently, but the underlying biophysical causes have not been unambiguously identified (Davis and Norman 1988). Enhanced crop growth, development and productivity are often attributed to microclimatic changes induced by windbreaks (e.g. Barker *et al*. 1985; Chaput and Tuskan 1990; Rasmussen and Shapiro 1990; Puri *et al*. 1992). However, such microclimatic changes are subtle and their effects on crop performance are often inconclusive, making agronomic and economic analyses difficult, if not impossible. Further, effects differ from season to season and hence experimental evidence is limited by the specific climatic conditions encountered during the period of data collection. These problems are compounded by the considerable spatial variability that exists in any field experiment, but particularly so when large areas, as in the case of natural windbreaks, are involved. Thus, any experimental program will be limited in its interpretive value by the edaphic and climatic conditions encountered during data collection. However, experimental data can be interpreted through simulation approaches, providing that the simulations (i) capture the underlying physical and physiological processes and (ii) are capable of reproducing experimental findings (Barker *et al*. 1985)

According to Cleugh (1998), the main mechanisms by which windbreaks modify micro-climatic parameters are: (i) modified wind speed and turbulence which alter the exchanges of heat, water vapour and CO_2 between the land surface and the atmosphere; (ii) the solar radiation regime is altered due to shading by a windbreak during the day and emissions of thermal radiation at night; (iii) changes to turbulence and radiation mean that temperature and humidity are modified; (iv) subsequent changes to soil evaporation and plant transpiration will modify seasonal water use and water use efficiency.

All these factors can affect crop growth and development. Some of these mechanisms operate incrementally over a growing season while others are intermittent. The importance of these mechanisms, and whether they play an incremental or intermittent role, will vary with region, season, cropping system and management. Field experimentation can be used to examine aspects of these effects, but it is difficult to reduce the complexities of natural systems to simple cause and effect. Simulation modelling can allow the objective assessment of the multi-site and multi-season consequences of microclimate modification by windbreaks.

In this paper we develop and validate a simulation approach to explore the impacts of windbreaks on crop growth and development. Specifically, we address the hypothesis that windbreaks influence the crop water and energy balances, thus affecting potential evapotranspiration and consequently plant growth. Our overall objectives are to: (i) develop a robust simulation capability that translates the impact of measurable differences in microclimate induced by windbreaks into physiological changes in crop growth, development and ultimately yield; and (ii) use this simulation capability to quantify the effects from the environmental changes induced by windbreak on yield and farm income throughout the cropping regions of Australia.

In this paper we will concentrate on the former objective, while the latter is addressed in the companion paper (Carberry *et al*. 2002).

Problem definition and methods

Background

As part of a larger research program (Cleugh *et al*. 2002), modelling approaches capable of simulating environmental changes behind windbreaks were developed and validated alongside detailed field experimentation (Sudmeyer *et al*. 2002; Wright and Brooks 2002). These approaches included a model capable of simulating the micro-meteorological changes induced by windbreaks (Cleugh 2002) and modifications to an existing cropping systems simulation capability that estimates windbreak effects on crop growth and ultimately yield (McCown *et al*. 1996; Meinke *et al*. 1997*a*). In a companion study, these simulation approaches are used in conjunction with long-term climate records to conduct an economic assessment of windbreaks on farms (Carberry *et al*. 2002).

To use crop simulation models operationally, their input requirements must be limited to environmental variables that can be easily measured and obtained. Most of the crop simulation models used operationally today require daily values of maximum and minimum temperature, solar radiation and rainfall as input. Although predictions by these models can often be improved by using, for instance, actual values for vapour pressure deficit (VPD) or wind speed as additional inputs, such measurements are rarely available as long-term daily records and hence model development has concentrated on building models around the 'standard' set of daily weather inputs (e.g. O'Leary *et al*. 1985; Hammer *et al*. 1987; Chapman *et al*. 1993). This is also the case for the Agricultural Production Systems Simulator (APSIM) suite of models that utilise transpiration use efficiency and radiation use efficiency as key parameters to calculate biomass accumulation and yield (de Wit 1958; Fischer 1979; Tanner and Sinclair 1983; Carberry *et al*. 1996; Meinke *et al*. 1997*a*, 1997*b*). Although these biological models have proven robust and useful for a very wide range of applications, they are not responsive to changes in wind speed and cannot be used to assess windbreak impacts without modifications.

In this paper, a physically and physiologically sound simulation approach is reported that allows the incorporation of wind speed differences behind shelterbelts into APSIM. This was achieved by: (i) developing a modified version of the Penman equation (Penman 1948; Doorenbos and Pruitt 1977) to replace the normal transpiration demand terms in APSIM; (ii) demonstrating that a modified Penman equation closely estimates daily transpiration demand when compared to a simulation model, SCAM (The Soil Canopy Atmosphere Model, Raupach *et al*. 1997), which is similar in form to the Penman–Monteith equation, but includes a full energy and water balance for the soil and canopy; (iii) implementing this validated approach in the new $APSIM_{EO}$ module, thus making it available to the entire suite of APSIM crop modules; and (iv) testing the performance of this new approach against the original transpiration efficiency approach.

Crop transpiration demand

In the APSIM suite of crop models, potential daily crop growth (C, g/m^2.day) is calculated as a function of solar radiation (R, MJ/m^2.day), the proportion of radiation intercepted (I), and the efficiency with which intercepted radiation is used (RUE, g/MJ):

$$C = R \times I \times RUE \quad (1)$$

where Beer's Law states that

$$I = 1 - \exp(-k \times LAI), \quad (2)$$

and where LAI is leaf area index (m^2/m^2) and k is the crop extinction coefficient. Under non-limited water conditions, crop transpiration demand (T_d, mm/day) is assumed driven by dry matter production:

$$T_d = C \times VPD/TE_c \quad (3)$$

where (TE_c, kPa g/m^2.mm) is the transpiration efficiency coefficient for above ground biomass, which is modified by VPD, the daily value of atmospheric saturation vapour pressure deficit (kPa). Values for VPD are estimated from the daily difference of maximum and minimum temperature (Tanner and Sinclair 1983). Meinke *et al*. (1997*b*) showed that this approach results in reliable estimates for wheat grown in Queensland. The value of TE_c is assumed to be constant for a crop species (Tanner and Sinclair 1983). Under water limited conditions, soil water supply (T_s, mm/day) does not meet crop water demand T_d and daily crop growth is driven by T_s:

$$C = T_s \times TE_c/VPD. \quad (4)$$

In the APSIM suite of crop growth models, transpiration is modified by changes in VPD under non-water-limited conditions (equation 3); under water-limited conditions, transpiration is driven by T_s. Wind speed does not affect transpiration under either condition. The ratio between potential soil water supply and demand (T_s/T_d) is then used to index the water status of the crop at any time. An index greater than unity indicates no water limitation. This index provides a biologically meaningful measure for the severity of water stress and is used to affect leaf area development and other physiological processes. Values reported for TE_c are usually of similar magnitude within crops and differences between species have been well established, but there is still considerable variability associated with its measurement. Although model results are sensitive to the value of TE_c, most simulated results conform well to experimental data across a wide range of environmental conditions. More details regarding this approach to simulating transpiration can be found in Fischer (1979), Tanner and Sinclair (1983), Monteith (1986), Sinclair and Horie (1989), Spitters (1990), Chapman *et al*. (1993) and Meinke *et al*. (1993, 1997*a*, 1997*b*).

Atmospheric demand

To account for the impact of wind speed on potential evapotranspiration, the Penman equation can be employed (Penman 1948). This is a method well suited to assessing the atmospheric demand for water in response to wind speed (e.g. Raupach and Finnigan 1988). While the Penman approach incorporates a sound understanding of the physical principles governing the atmosphere–plant continuum and the surface energy balance, biological responses and biological principles are not considered. Hence, Monteith (1965) and Monteith *et al*. (1965) developed the Penman–Monteith equation which incorporated physically based responses of leaf stomata to water limitation. While this approach lacks some of the physiological responses observed in plants, it does account sensibly for variations in the energy balance (and hence wind speed) at any given location, providing the necessary parameters can be derived from calibrations against field data.

SCAM (Raupach *et al*. 1997) was originally based on the Penman–Monteith equation, but extensively modified to enable a full soil and canopy energy and water balance to be simulated. SCAM is used to predict both the flows of energy and water through the soil–plant–atmosphere continuum and can address the spatially varying microclimate fields around a windbreak. SCAM is a 1-dimensional model of land–atmosphere exchanges of energy and water. It includes a plant canopy that intercepts radiation and rainfall; evaporates and transpires intercepted water and water from the soil water store. The interaction between soil and plants is simulated using an energy and mass-balance approach (i.e. both energy and water are conserved) and incorporates parameterisations for within canopy turbulent transfer processes. Running on a 15-min to hourly time-step, SCAM provides an appropriate balance of physical complexity and realism, in terms of linking airflow, radiation, heating and evaporation processes in a plant–atmosphere continuum. However, SCAM lacks the ability of the APSIM-style models to simulate physiological differences between crops or the influence of crop phenology, crop management and nitrogen nutrition on leaf area development, biomass accumulation and ultimately crop yield. All these are essential requirements for the simulation of on-farm crop yields. Further details relating to SCAM can be found in Cleugh (2002).

Reconciling crop and atmospheric demand terms

As discussed in the previous sections, neither APSIM nor SCAM were suitable for assessing windbreak effects on crop growth. Connecting the 2 approaches dynamically was also inappropriate due to the differences in time-steps (daily *v.* 15-min) and the detailed input data requirements of SCAM. An iterative set of connections between the 2 models was possible, whereby APSIM was used to provide daily leaf area index estimates for SCAM, which were then used to estimate daily transpiration demand in response to specific climatic conditions, including wind speed. This demand term was then fed back into APSIM, with consequences on dry matter accumulation and yield. While this method can be employed whenever 15-min environmental data were available, it was unsuitable for assessing long-term economic consequences of windbreaks at a range of locations. It does, however, overcome the feedback problems on LAI estimates that were encountered when SCAM estimates were used directly by APSIM to simulate dry matter production.

Inevitably, the TE-based approach to estimating daily water demand will differ for different crops experiencing the same climatic conditions due to crop-specific parameter values for the 2 key parameters RUE and TE_c (de Wit 1958; Fischer 1979; Tanner and Sinclair 1983). In the APSIM-I_Wheat module, these parameter values are 1.34 g/MJ and 4.7 g/m^2.mm kPa, respectively (Meinke *et al*. 1997*a*). The corresponding values for APSIM-Mungbean are 0.95 g/MJ and 5.5 g/m^2.mm kPa, respectively (M. Robertson pers. comm.). Such TE-based models provide reliable estimates of dry matter production and yield over a wide range of environments without environment-specific calibration (Meinke *et al*. 1997*a*)

To be able to simulate effects of altered wind speed on crop growth, a modified version of the Penman equation was incorporated into the $APSIM_{EO}$ module and was used to estimate potential evapotranspiration demand. Partitioning of potential evapotranspiration into a daily crop transpiration demand was achieved by multiplying potential evapotranspiration by daily values of relative green cover (values ranging from 0 to 1). The $APSIM_{EO}$ approach captured the physical aspects of atmospheric conditions and combined them with the crop physiological concepts of the TE-based modules in APSIM (in this paper the standard TE approach in APSIM is termed $APSIM_{TE}$).

Sensitivity to changes in VPD and solar radiation differ when calculating water demand based either on a TE or EO approach. These differences are a consequence of different response functions and their resulting interactions between modelling approaches (cf. equation 3 *v.* 5). This explains why estimates of potential demand using either the TE or EO approach are fairly similar under low VPD conditions and over a range of radiation and wind speed levels. However, potential crop transpiration demand calculated based on TE increases above that estimated by EO when either VPD or radiation increases to very high levels. Such effects have been measured in crops experimentally and explained theoretically (Tanner and Sinclair 1983).

For 2 crops and at 2 locations (wheat and mungbean grown at Hermitage, Queensland and wheat grown near Esperance, Western Australia), the Penman equation was calibrated using SCAM simulations. Crop- and site-specific calibration of this approach is needed for 3 reasons: (i) Differences in sensitivity to changes in VPD and radiation must be overcome; (ii) The energy and aerodynamic terms of the Penman equation (equation 5) were developed for medium to high solar radiation and relative humidity conditions and for wind runs that were about double during daylight hours compared to night conditions. Such conditions are not always met, hence environment specific calibration is necessary (Doorenbos and Pruitt 1977); (iii) Crop and site-specific differences between the approaches can be accounted for with the help of a single calibration factor (β, equation 5).

Implementation of the modified Penman equation in APSIM

The Penman model as modified by Doorenbos and Pruit (1977) was implemented as a new $APSIM_{EO}$ module in version 1.54. The modification accounts for the fact that at many locations about 66% of daily wind run occurs during daylight hours. In the $APSIM_{EO}$ implementation, day : night wind ratio was assumed to equal 2, except when the day wind speed fell below 1 m/s. On such days it was set to 1, thus evaporative demand was considered not to change below this speed due to advection. This simplification avoids possible instabilities in the model at very low wind speed for which no experimental data were available.

The Penman model as modified by Doorenbos and Pruit (1977) has been implemented as:

$$ET_o = \beta \times c \times 1000 \times [\varepsilon \times R_n \times d + \lambda \times f(U_2) \times VPD] / [\lambda \times \rho \times (\varepsilon + 1)] \quad (5)$$

where ET_o is reference potential evapotranspiration (mm/day), β is crop calibration factor, accounts for differences in TE and RUE, c is tabulated adjustment factor to compensate for day/night weather conditions, ε is the dimensionless slope of saturated specific humidity at a given temperature, $Q_{sat}(T)$.

$$\varepsilon = \lambda / c_p \times dQ_{sat}/dT \quad (6)$$

where Q_{sat} is the saturation specific humidity, which is a function of temperature (T) and c_p is the specific heat of air. R_n = net radiation (W/m^2) = ($R_S + R_L$), d is duration of daylight (s), λ is latent heat of vaporisation for water (J/kg), $f(U_2)$ is Doorenbos and Pruit modified Penman wind function = $0.027 \times (1 + 0.01 \times U_2) \times 10$ (kg/m^2.hPa.day), U_2 is wind speed at 2 m height (km/day), with a minimum of 86.4 km/day applied, VPD is vapour pressure deficit (hPa) = $0.75 \times (e^*_{Tmax} - e^*_{Tmin})$, e^*_{Tmax} is saturation vapour pressure at maximum temperature (hPa), e^*_{Tmin} is saturation vapour pressure at minimum temperature (hPa), ρ is density of water (kg/m^3).

Table 16 of Doorenbos and Pruit (1977), assuming U_{day}/U_{night} wind ratio of 2, was implemented to estimate c, using incoming short wave radiation (R_S), relative humidity (RH, equation 7) and daytime wind speed (U_{day}, equation 8). The incoming short wave radiation was measured, relative humidity calculated from maximum and minimum temperatures and daytime wind speed from daily wind run, assuming 0.66 of that wind occurs during the day.

Relative humidity was calculated according to Tanner and Sinclair (1983):

$$RH = e^*_{Tmin}/e^*_a \quad (7)$$

where e^*_{Tmin} is saturation vapour pressure at minimum temperature (hPa) (note that this simulates the average daily vapour pressure), e^*_a is daytime saturation vapour pressure (hPa) = $0.75\, e^*_{Tmax} + 0.25\, e^*_{Tmin}$, and

$$e^*_a - e^*_{Tmin} = 0.75(e^*_{Tmax} - e^*_{Tmin}) = (0.75\, e^*_{Tmax} + 0.25\, e^*_{Tmin}) - e^*_{Tmin}.$$

Daytime wind speed was calculated as follows:

$$U_{day} = \text{daytime wind speed (km/h)} = 0.66\, U_2/d_{12} \quad (8)$$

where d_{12} equals 12 h of daylength. An additional multiplier on U_2 was also implemented to enable simulations for any amount of wind-speed reduction at various heights behind a windbreak.

Longwave radiation is calculated as follows:

$$R_L = (E_a - 1) \times \sigma \times (T + 273)^4 \quad (9)$$

where E_a is clear sky emissivity, σ is the Stefan-Boltzmann constant ($5.67/10^8$ $W/m^2.K^4$) and T is the average daily temperature in C.

E_a was calculated as follows:

$$E_a = 0.7 + 5.95/10^5 \times e_a \times 2.718282^{[1500/(T + 273)]} \quad (10)$$

where e_a is the vapour pressure in hPa.

Model validation

The theoretical approaches described above were tested against field data from artificial shelter experiments (Sudmeyer *et al*. 2002). The data consisted of detailed environmental measurements of crop growth and yield for wheat and mungbean taken from artificial enclosures in south-eastern Queensland and in south-eastern Western Australia. Sudmeyer *et al*. (2002) describe in detail the design of these artificial shelters, and the measures taken to minimise errors associated with shading. For open field conditions $APSIM_{TE}$ closely simulated the experiments. Hence, $APSIM_{TE}$ runs were used as baseline datasets to validate the $APSIM_{EO}$ approach and derive the appropriate value for β. For sheltered conditions, daily evapotranspiration and transpiration demand estimates from $APSIM_{EO}$ were compared against SCAM output to validate the model's performance under reduced wind conditions. Finally, $APSIM_{EO}$ was run at 2 sites using long-term climate data to assess the likely year-to-year variability of windbreak effects on crop yields.

Results

$APSIM_{EO}$ v. *SCAM*

Sudmeyer *et al*. (2002) showed that wind speed within the artificial enclosures was reduced by about 70% regardless of season or location. This represents the maximum wind reduction possible by windbreaks and data from these experiments is ideally suited to benchmark model responses.

Using experimental data for wheat (1997) and mungbean (1998) at Hermitage, Queensland (28.6°S, 151.9°E, 475 m) and wheat (1997) at Esperance, Western Australia (33.8°S, 121.9°E, 25 m), both $APSIM_{EO}$ and SCAM were run for these experiments and their transpiration demand estimates compared. Measured LAI data, interpolated to daily LAI estimates were used as input into SCAM to overcome its inability to dynamically simulate crop development. Figure 1 shows the time-course of daily transpiration demand estimated using $APSIM_{EO}$ and SCAM for both open field conditions and total shelter. Corresponding regression slopes and R^2 values are shown in Figure 2 and show a general trend, whereby SCAM estimates are higher that $APSIM_{EO}$ for wheat, but lower for mungbean. No clear difference in performance between these 2 methods of estimating transpiration demand is apparent.

The close correspondence of daily transpiration demand simulated by $APSIM_{EO}$ and SCAM demonstrated that the simpler $APSIM_{EO}$ approach was an adequate surrogate for

SCAM (Fig. 1). This result permitted the incorporation of the effects of wind speed into the APSIM-style models, on the condition that both approaches gave similar differences between demand estimated for open field conditions and within the artificial enclosures (Table 1).

$APSIM_{EO}$ v. $APSIM_{TE}$

While $APSIM_{EO}$ compared well for estimates of transpiration demand with SCAM, it must also perform adequately in terms of the baseline set by $APSIM_{TE}$ in simulating dry matter accumulation and final yield. Hence, both $APSIM_{EO}$ and $APSIM_{TE}$ were tested against long-term simulations for wheat, maize or mungbean at 17 locations throughout Australia. Here we will only present results for 2 locations in detail. For further details see Carberry *et al.* (2002)

As pointed out earlier, the $APSIM_{EO}$ approach needed to be calibrated for individual crops and environments to give reliable dry matter and yield estimates (Doorenbos and Pruitt 1977; Tanner and Sinclair 1983). This was achieved by changing values of parameter β until yield and transpiration demand estimates for open field conditions were similar to those obtained using $APSIM_{TE}$ with at least 13 years of climatic data at each location. The range of calibration values for β for wheat, mungbean and maize throughout the main cropping regions of Australia are presented in Carberry *et al.* (2002). Here we restrict presentation to the 2 experimental sites at Hermitage and Esperance. Each crop and site combination required this calibration to ensure $APSIM_{EO}$ predicted similar water use and crop yields to $APSIM_{TE}$.

Using daily climate records from 1970 to 1997, Figure 3 shows the result of this calibration process for wheat and mungbean at Hermitage and for wheat at Esperance. For wheat, a β-value of 1.0 resulted in best fits at Hermitage, while at Esperance a value of 0.85 was necessary to achieve

Table 1. Regression slope and R^2 values for relationships between transpiration demand inside the enclosures *v.* demand for open field conditions as predicted by both $APSIM_{EO}$ and SCAM

	$APSIM_{EO}$		SCAM	
	Slope	R^2	Slope	R^2
Hermitage, wheat	0.90	0.93	0.93	0.99
Hermitage, mungbean	0.92	0.98	0.95	0.99
Esperance, wheat	0.90	0.98	0.91	0.99

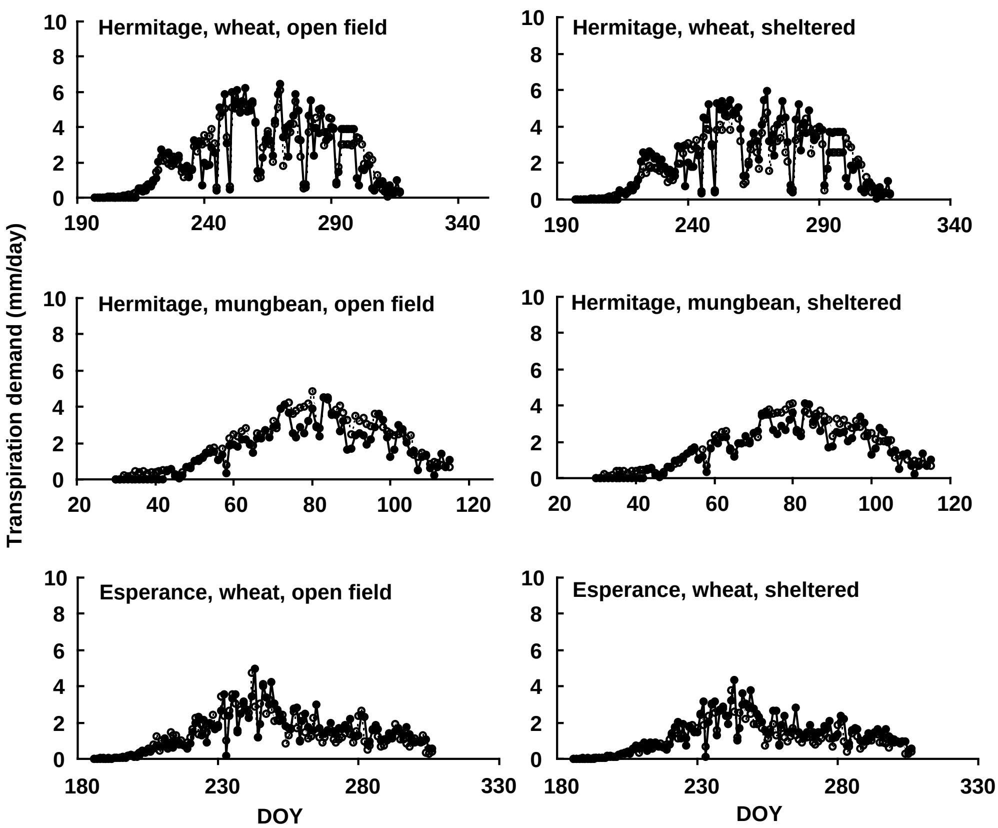

Figure 1. Daily estimates (day of the year, DOY) of transpiration demand in 1997 (wheat) and 1998 (mungbean) by $APSIM_{EO}$ (open symbols) and SCAM (closed symbols) before calibrating for crop- or site-specific conditons (i.e. β = 1.0). Shown are simulations for Hermitage, Qld (wheat and mungbean), and Esperance, WA. Panels on the left represent open field conditions, while panels on the right represent conditions inside the artificial shelters.

good correspondence between yield estimates. For mungbean (Hermitage only) a value of 0.92 resulted in the best fit. Simulated biomass and yields of $APSIM_{TE}$ and $APSIM_{EO}$ after calibration were generally distributed around the 1:1 line with R^2 values ranging from 0.92 to 0.97 (Fig. 3).

Once the necessary parameter values for β were established from long-term, independent climate data, $APSIM_{EO}$ was run to simulate the artificial shelter experiments and its performance was compared against measured field data. Under open field conditions there was little (wheat) to no difference (mungbean) in simulated dry matter accumulation between $APSIM_{TE}$ and $APSIM_{EO}$ (Fig. 4). Yield was also simulated well with only small differences between the 2 methods (Fig. 5). For crops grown in artificial enclosures we compared 2 methods of estimating the effects of wind reduction on crop growth. Sudmeyer *et al.* (2002) showed that throughout the growing season and irrespective of location or crop, wind speed within the enclosures was reduced by about 70%, compared to open field conditions. Hence, $APSIM_{EO}$ was run using either actual, daily wind run measured within the shelters or open-field windrun reduced by a set 70%. The 2 methods produced very similar results, particularly in terms of total dry matter production (Fig. 4). Yields were generally 1–5% lower than those estimated from $APSIM_{EO}$ when using the 70% reduction method and closely matched the observed values (Fig. 5).

Evaluation of long-term, seasonal difference

The sensitivity of crop growth to wind reduction will depend strongly on the type of season encountered. Micrometeorologically induced shelter effects are likely to be greater in seasons with moderate to severe water stress (Kort 1988). To test year-to-year variability, Carberry *et al.* (2002) identified sites around Australia that had at least 13 years of recorded, daily windrun. Here $APSIM_{EO}$ was tested at 2 of these locations to demonstrate its ability to evaluate long-term consequences of windbreaks on crop productivity — simulations were undertaken for wheat and mungbean at Hermitage over 33 years and for wheat at Esperance over 29 years.

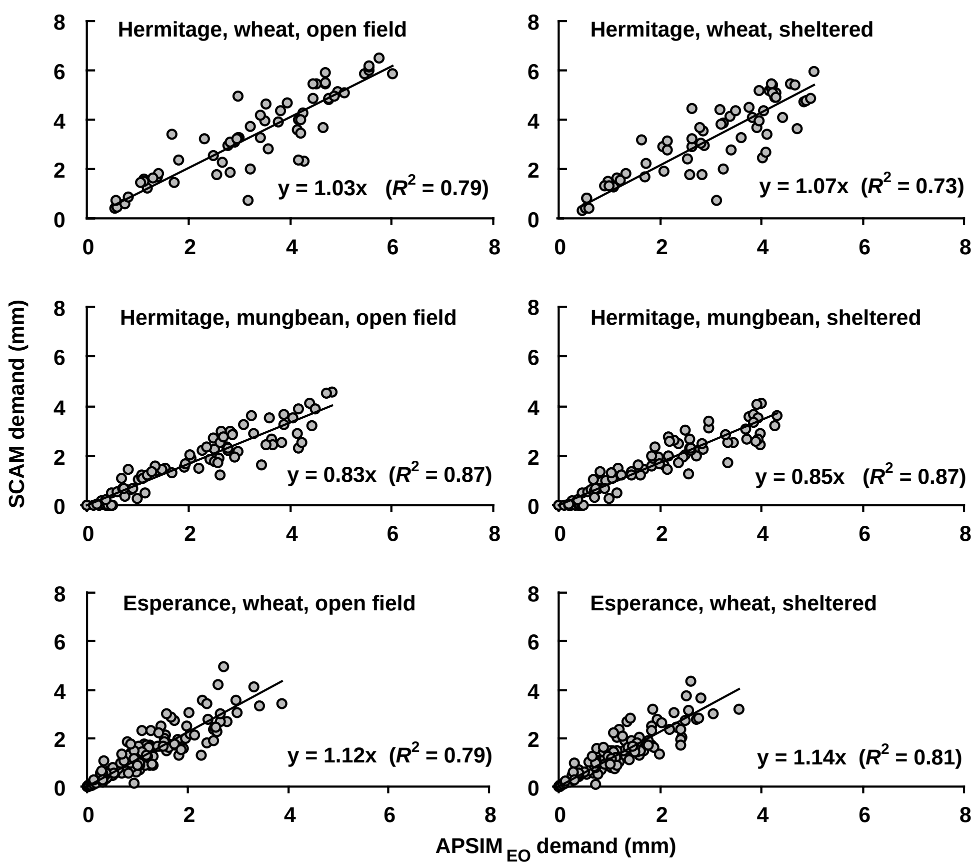

Figure 2. Daily estimates of transpiration demand by $APSIM_{EO}$ and SCAM before calibrating for crop- or site-specific conditons (i.e. β = 1.0). Shown are daily estimates for Hermitage (wheat and mungbean) and Esperance. Panels on the left represent open field conditions, while panels on the right represent conditions inside the artificial shelters.

The 70% reduction in wind speed behind artificial shelters (Sudmeyer *et al*. 2002) would represent the maximum shelter achievable by any windbreak. Therefore, for the following simulations, a 70% reduction in wind speed was assumed in order to represent the optimum windbreak effect at these 2 locations. At Hermitage, the average yield improvement was 13% for wheat and 3% for mungbean. For wheat at Esperance the average yield improvement from reduced wind speed was 5% (Fig. 6). In any year, however, effects varied from negative, neutral to positive, highlighting the highly variable nature of the expression of windbreak effects. In addition to the windbreak effect, these simulations also demonstrate the strong environmental differences between Hermitage and Esperance. While average simulated wheat yields for open field conditions were only slightly higher at Hermitage (344 *v.* 296 g/m^2), associated standard deviations are 7 times higher at Hermitage (210 *v.* 33 g/m^2).

Discussion

Shelter effects on microclimate and subsequent impacts on crop growth and development are difficult to establish experimentally (Wright and Brooks 2002; Sudmeyer *et al*. 2002; Nuberg *et al*. 2002). Effects are often small, subtle or non-existent, while spatial and climatic variability and the heterogeneity of plant populations can be considerable (Carberry *et al*. 2002). An appropriate modelling approach can help to elucidate the biophysical processes involved as well as estimate the long-term shelter effects on crop productivity. While the consequence of wind reduction by windbreaks on micrometeorological parameters can be

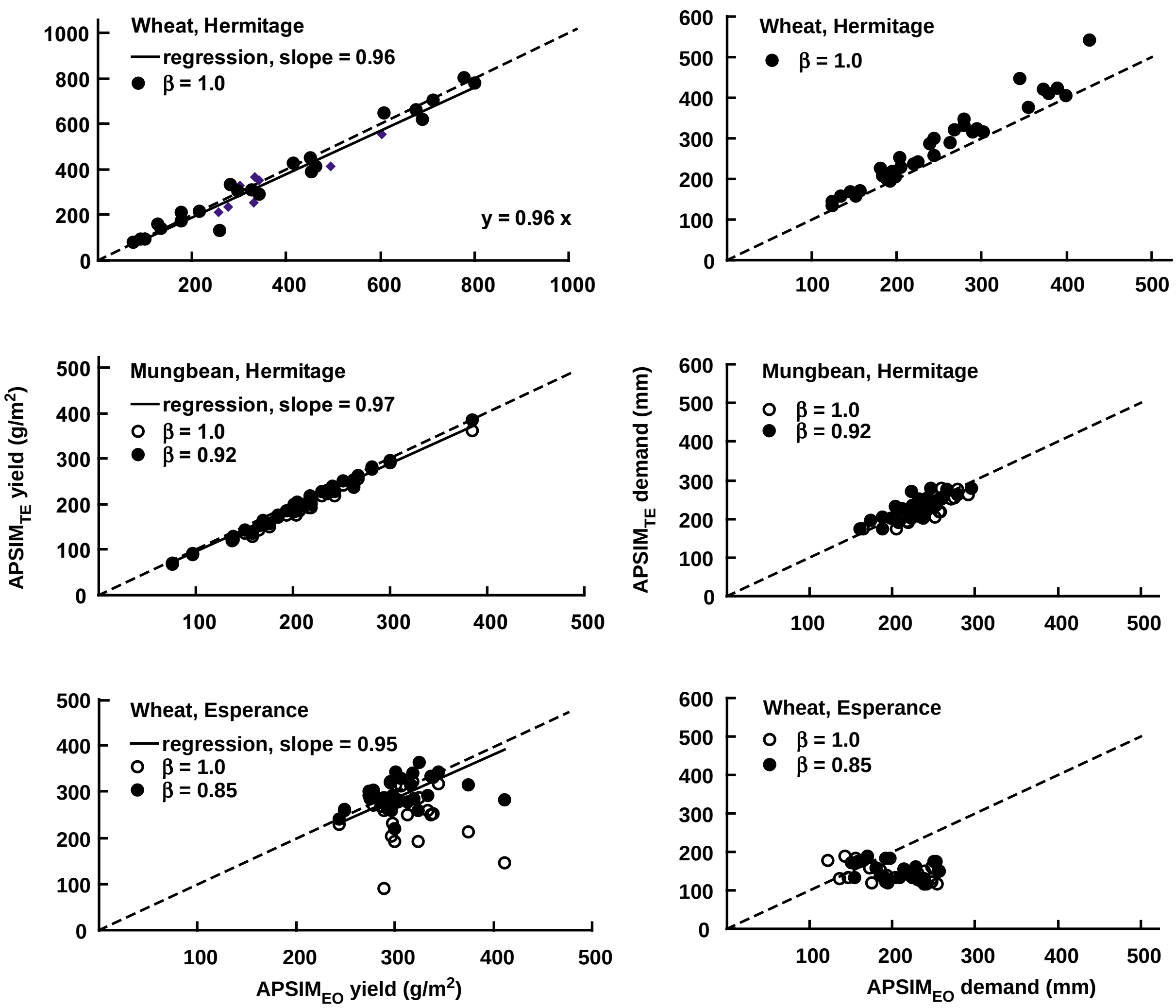

Figure 3. Effect of calibration of parameter β on yield and transpiration demand for wheat and mungbean at Hermitage (top and centre panels, respectively) and wheat at Esperance (bottom panels). Cumulative seasonal transpiration demand from $APSIM_{EO}$ was calibrated so that yield predictions by $APSIM_{TE}$ and $APSIM_{EO}$ were as similar as possible based on the 28-year calibration period (1970–97). This was achieved by using an adjustment factor (β) on daily transpiration demand. Shown are simulations before calibration (i.e. β = 1.0) and after calibration. Note that for wheat at Hermitage (top panels) a β-value of 1.0 resulted in the best fit.

quantified and simulated (Cleugh 2002), their subsequent impact on biological systems is more difficult to quantify and predict. Physically based models, such as the Penman–Monteith equation or SCAM, can help to better understand underlying processes but they are not designed to capture biological responses caused by crop physiological interactions and dynamics. Conversely, biological models such as in APSIM can be useful in capturing physiological interactions but are usually not designed to account for factors such as wind speed when estimating growth and development.

In this study, both the physics and the underlying biology were captured at a level that was both meaningful and useful. In the case of windbreaks and their consequences for crop productivity, a complex, physical approach to the soil–plant–atmosphere energy balance was simplified in order to bring it in line with the crop physiological level of the APSIM suite of crop simulation models (e.g. Hammer and Muchow 1994; Carberry *et al.* 1996; Meinke *et al.* 1997*a*). The suitability of this modelling approach to investigate complex, biological interactions is apparent from its use in plant breeding and cropping systems design (Chapman *et al.* 1996; Hammer *et al.* 1996*a*, 1996*b*; Hammer 1998), environmental and production risk assessment (Keating and Meinke 1998) and strategic cropping systems decision making (Carberry *et al.* 2000).

This study has shown how physical and biological approaches can be combined to aid our understanding of systems processes. Both the environmental physics perspective and the biological perspective have shortcomings when issues that sit at the interface of both approaches need to be addressed. While the physical approach has clear advantages when investigating changes in

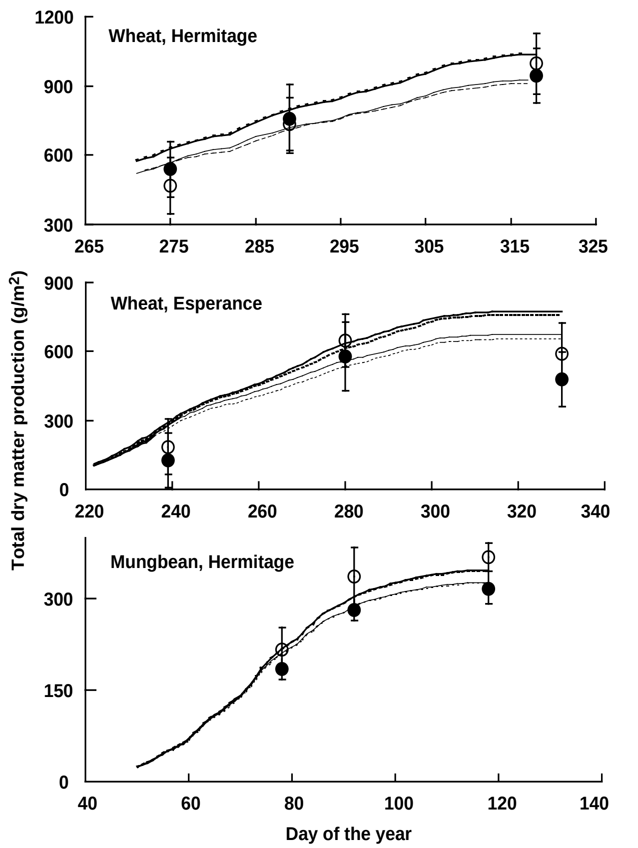

Figure 4. Time course (day of the year) of actual and predicted total dry matter production for open field conditons (O) and complete shelter (S) for wheat and mungbean at Hermitage and wheat at Esperance. Error bars on measured experimental data (Ex) are shown as ± 1 standard deviation. Simulation output from $APSIM_{EO}$ is indicated by EO and output from $APSIM_{TE}$ by TE. $APSIM_{EO}$ simulations based on open field conditions, but with wind speed reduced by 70% are shown as EO_r. In the case of mungbean, the different approaches to simulating open and closed conditions are so similar that lines could not be distiguished. O_Ex (●), S_Ex (○), O_TE (…), O_EO (—), S_EO (━━) and EO_r (- - -).

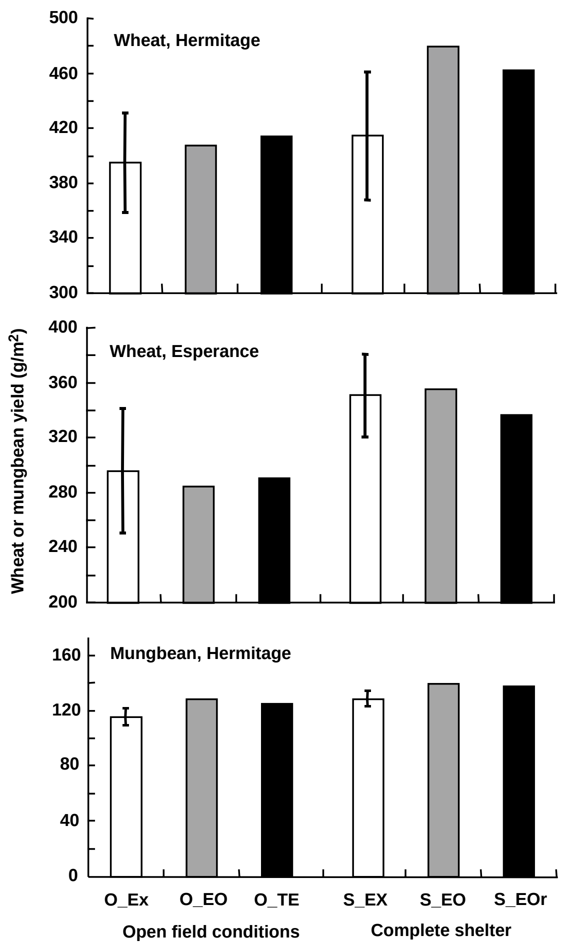

Figure 5. Actual and predicted yield for open field conditons (O) and complete shelter (S) for wheat at Hermitage and Esperance and for mungbean at Hermitage. Error bars on measured experimental data (Ex) are shown as ± 1 standard deviation. Simulation output from $APSIM_{EO}$ is indicated by EO and output from $APSIM_{TE}$ by TE. $APSIM_{EO}$ simulations based on open field conditions, but with wind speed reduced by 70% are shown as EO_r.

physical parameters such as wind speed, VPD, temperature or the energy balance of the soil–plant–atmosphere continuum, it cannot deal with complex, biological systems adequately. Conversely, the crop physiological approach can handle such biological interactions in a scientific and robust way while certain atmospheric processes are not considered. The challenge was not to try and capture all these effects in 1 model, but rather to structure a modelling approach in a way that allowed for inclusion of such processes where necessary. The approach used a phenomenological

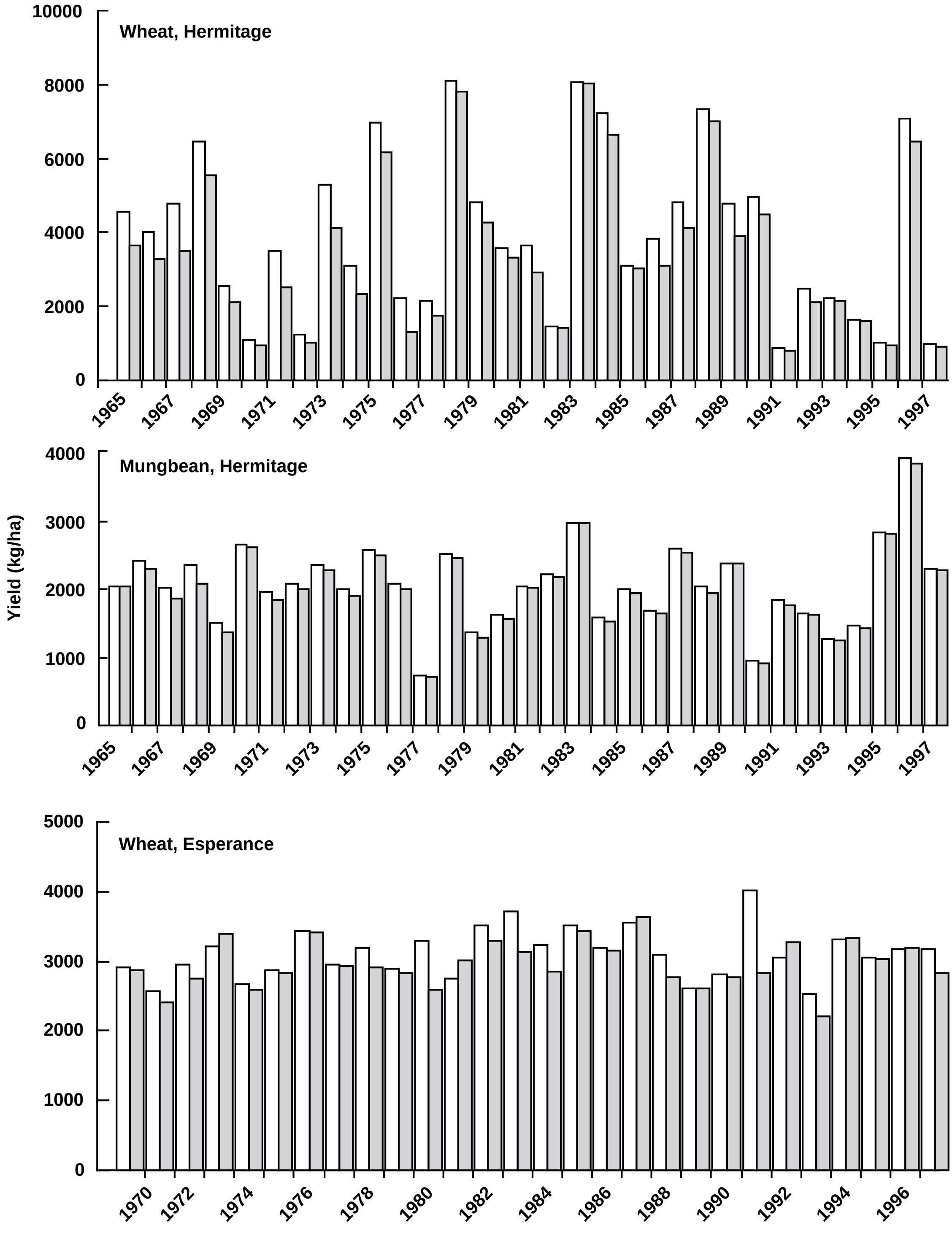

Figure 6. Twenty-year yield simulations for Hermitage (wheat and mugbean) and Esperance (wheat) for open field conditons (shaded bars) and complete shelter (open bars). Shelter increased yield on average by 13, 3 and 5%, respectively.

description of evapotranspiration sensitive to wind speed and validated its performance against: (i) the SCAM model which contains well tested, physical relationships to describe micrometeorological processes; and (ii) APSIM which has been well-tested and applied to describe crop physiological processes. The level of complexity chosen was determined by the intended use of the model for multi-season impact assessments (Carberry *et al*. 2002). This required a simplified approach to allow such applications with the limited, long-term data available (i.e. daily inputs of weather variables). To reduce number and uncertainty of parameters in simulating biological systems, a process-based approach can be replaced by a phenomenological description of that process without sacrificing scientific principles. This requires that: (i) the process is already understood at the more basic level, and (ii) the phenomenological description is general across a wide range of conditions and of low complexity with easily derived parameter values (Spitters 1990). Here we have shown that such a phenomenological process description can be used to connect a detailed, physical approach using a 15-min time-step with a standard, biological approach of modelling crop growth and development using a daily time-step.

The artificial shelter experiments described by Sudmeyer *et al*. (2002) were specifically designed to obtain the maximum shelter effect and associated crop physiological responses. Being able to reproduce these experimental findings with $APSIM_{EO}$ not only is a test of this approach, but also provides the capacity to simulate other experiments where detailed data were collected along transects behind natural windbreaks (Prinsley 1992). Although simulation results indicated that average yield improvements could be in the order of between 3 and 13% for maximum shelter conditions (70% wind speed reduction), the real impact of natural shelter belts will be considerably less. This is a consequence of: (i) the difficulty in providing high levels of shelter to crops growing more than 5 H from a windbreak, and (ii) winds blowing oblique to the shelter, further reducing its effectiveness (Cleugh 2002). Consequently, experimental evidence of yield increases behind shelter belts is difficult to obtain and highly variable — frequently the changes predicted by $APSIM_{EO}$ were within the error of experimental measurements. The $APSIM_{EO}$ approach can now be used to assess the likely effects of windbreaks on crops at a range of locations around Australia (Carberry *et al*. 2002).

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